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A Review of Recent Impact Sensitivity and Hot Spot Investigations

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ABSTRACT

During the past few years, at the Naval Surface Weapons Center, there has been an effort to understand the basic processes responsible for hot spot formation and ignition in solid propellants and explosives under impact loading conditions. This effort has resulted in the development of a new and versatile impact machine as well as a number of new instrumentation techniques. Shear and fracture have been identified as the most likely sources of hot spot generation. A fundamental understanding of the processes responsible for shear induced energy localization and potential hot spot generation has been obtained. This paper reviews these results as well as some recent developments in the related areas of explosive response and heating due to cracking.

INTRODUCTION

The problems and frustrations associated with impact machines are well known to all those who are familar with explosive safety testing. In this paper, we review some of the more recent impact machine developments at the Naval Surface Weapons Center (NSWC) which shed some light on these problems. The effort at NSWC is aimed at furthering our basic understanding of the processes responsible for hot spot formation and ignition in solid propellants and explosives due to impact-like loading conditions. Many of the problems and apparent contradictions which in the past have been associated with impact machines were really due to an inadequate understanding of these basic processes. While there is still much to learn, we are now in a position to dispel some of the confusion associated with impact testing.

We begin by providing an analysis of the forces on the impact machine which is sufficiently general to be applicable to most of the commonly used impact machines. With these results in hand, we describe the design philosophy on which the new NSWC impact machine was built, and briefly describe its capabilities. Early in the project it was realized that

to be of any value, the impact machine had to be adequately instrumented. This instrumentation, much of which was designed simultaneously with the design of the new impact machine, will be described.

In parallel with these efforts, other efforts were made to understand the fundamental processes that are responsible for hot spot formation under impact loading conditions. It was shown experimentally that shear is the most likely cause of hot spot formation, and that pressure apparently has no direct role to play other than to provide a driving force for the shear motion. This data will be reviewed. At the same time, in a theoretical effort, it was shown that the action of shear and sudden failure of an impacted crystalline sample can be understood in terms of an avalanche of rapidly moving dislocations. This avalanche, associated with the sudden mechanical failure of the crystal under impact, produces a large amount of local deformation and local heating. These local hot spots are potential ignition sites. An overview of these results is given. Also, current research in the areas of explosive response and heating at the tip of a propagating crack will be briefly discussed.

It is to be re-emphasized that this work is research oriented and not testing oriented. We did not run large numbers of samples nor did we use the Bruceton Up-Down Method or similar methods to determine sensitivity drop heights. We did run large numbers of tests to determine if the impacts were repeatable, which they were. All experimental results were repeated at least 5 to 10 times to establish constancy. Equally important, we do not have all of the answers to questions concerning the impact machine, more remains to be learned. Getting on with this task is important not only for the fundamental reasons mentioned above, but also it is beginning to appear likely that the small scale, well instrumented, impact experiments and their derivatives may be able to provide insights into the events that lead to hot spot formation and ignition in large scale experiments. Because of their ultimate destructiveness, large scale experiments are, and likely will always be, both very expensive and very difficult to instrument.

ANALYSIS OF IMPACT MACHINE

Attempts to understand the response of energetic materials in an impact machine are of little value unless the bare tool response of the machine is understood. This is so because the bare tool response determines to a large degree the rate and amplitude of loading that the sample experiences. There are several ways of treating this problem, the most accurate of which would be a detailed computer code analysis. This approach, it turns out, is an unnecessary overkill. We have found that a satisfactorily accurate approach, that emphasizes the physics of the impact process, is to treat the machine as a collection of mass-spring elements with one element for each component of the impact machine.[1] Thus, an impact machine consisting of a drop weight, a striker-anvil, and a massive base, can be simplified by treating these components as a series of mass-spring systems as shown in Figure (1).

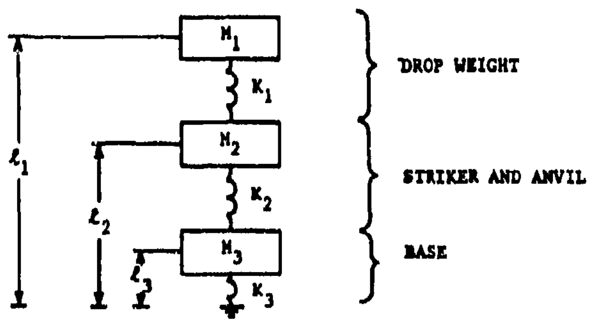

Figure 1. Lumped Mass-Spring Elements

If the striker has a rounded end on which the drop weight impacts, this feature can be treated as an additional Hertzean (non-linear) spring. We will not treat this case here since most of our impact machine design/configurations have no strikers for reasons which will become apparent shortly. For each mass-spring system there is an equation of motion. In the case of the impact machine represented in Figure 1 there are three equations of motion.

$$M_1\ddot{X}_1 = - K_1(X_1 - X_2 - X_3)$$

$$M_2\ddot{X}_2 = - K_2 (X_2 - X_3) + K_1 (X_1-X_2-X_3)$$

$$M_3\ddot{X}_3 = - K_3X_3 + K_2 (X_2 - X_3)$$

where

$$X_1 = \ell_1 (t) - \ell_1(0)$$

$$X_2 = \ell_2 (t) - \ell_2(0)$$

$$X_3 = \ell_3 (t) - \ell_3(0) \quad ,$$

These are coupled oscillator equations in which the natural frequency of each element has the form $\omega = \sqrt{\frac{K}{M}}$; K is the spring constant and M is the mass of each element. The typical impact machines have bases whose mass exceeds, by several orders of magnitude, the masses of the striker-anvil and drop weight. Therefore the base can be treated as immovable because the response time of the massive base is much longer than that of the striker-anvil or drop weight systems. The remaining two equations can be solved using Laplace Transform techniques to give the displacement of the striker-anvil as[1]

$$x_2(t) = \frac{K_1}{M_2} \dot{X}_1(0) \left[\frac{1}{\Gamma^2-\beta^2}\right]\left[\frac{1}{\beta} \sin \beta t - \frac{1}{\Gamma} \sin \Gamma t\right] .$$

The force on the striker-anvil is just $F_2(t) = K_2x_2(t)$. The total force is the sum of the forces due to oscillations of both the drop weight and the striker-anvil. When these forces go negative, rebound occurs and the analysis is stopped at this point since rebound is not of interest to us. The agreement between the above predictions and experiment has been checked for striker masses of 25 grams to 2.5 kg and has been found to be quite good.[1]

When three or more mass-spring elements are included in the analysis or when a curved interface is present, the problem can be easily solved by a numerical analysis scheme similar to that used in one-dimensional hydrodynamic code modelling. Models of this approach have been solved with four mass-spring pairs on a programmable hand calculator.

From these results, it is apparent that the combined ringing of the drop weight and striker-anvil can add to give a rather complicated force history. In order to simplify the loading history that a sample

would experience, in designing the new NSWC impact machine, we chose to operate either without a striker, in which case the sample is covered with a thin metal or plastic shim, or with only a very low mass striker ($\approx$25 gm). For bare tools this results in a clean nearly half sine wave loading pulse whose period is determined mainly by the natural frequency of the drop weight. There is yet another, equally compelling, reason to avoid the use of massive strikers and that is that although an explosive sample may have sufficient strength to support the weight of the striker, it is really quite soft compared with the loading forces of impact. Thus, on impact, the striker sees a relatively soft sample, and so initially moves away from the impacting drop weight with about twice the velocity of the drop weight. The sample is squashed, expanding until it can support the force of the striker whereupon the striker rebounds, and flies free for a short while. Shortly thereafter the striker reencounters the still downward moving drop weight from which it rebounds and strikes the sample again. This sequence can occur as many as 3 to 5 times during a single drop, and in any one of these cycles the sample might react. When multiple impact occurs, it is very difficult to interpret the actual cause of the initiation.

Our current impact machine has a choice of drop weights ranging from 1 kg to 10 kg. These give impact loading duration from 120 to 400 μs. The smaller weight is designed to give impact stress pulse rise times of about 5 μs which is approaching the stress pulse rise time of the Hopkinson bar. The impact machine, shown schematically in Figure 2, stands about 2 m high. In order to get higher effective drop heights, the weight can be accelerated by elastic shock cords. In this way, drop heights in excess of 20 m can be obtained with a 1 kg drop weight.

To avoid the uncertainties often associated with samples in the form of loose powders, we generally employ samples in the form of pellets 5 mm in diameter by 1 mm high. This size permits the sample mass to be approximately equal to the 35 mg used in the ERL-Bruceton machine. With a 5 kg drop weight; the NSWC machine repeatedly sets off dried PETN pellets at an 8 or 9 cm drop height and TATB pellets at an equivalent drop height of nearly 5 m.

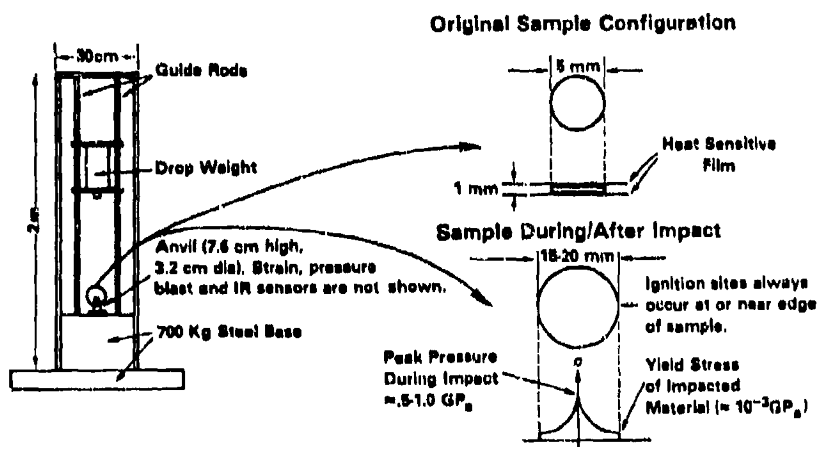

Figure 2. Schematic of NSWC Impact Machine

The pressure profile across the diameter of the pellet during impact has been determined both analytically and experimentally.[1,2] It has been shown that the pressure during impact has a maximum value at the center of the pellet disc and falls rapidly to the yield stress at the edge of the disc. During a typical impact, say from releasing a 5 kg drop weight from 100 cm, the peak pressure at the center of the disc may reach 1.0 Gpa (10 kb) and fall to a typical yield stress of perhaps 150-300 psi. It is straightforward to show that during impact the shear strain and shear strain rate attain maximum value at the outer edge of the impacted disc. What is significant is that at the threshold, ignition always occurs in the region very near or at the edge of the sample disc in the region of lowest pressure and highest shear. The experiments showing this will be described shortly.

It has been determined that ignition sensitivity is dependent on rate of loading. Thus, different impact machines with drop weights

and strikers of different natural frequencies will have different loading rates for a given drop height. Consequently, because of the dependence of sensitivity on loading rate, these machines will report different sensitivity drop heights. For example, when no strikers are present, RDX pellets can be set off with a 5 kg drop weight released from 27 cm. Taking a somewhat extreme case in which six strikers of various masses were inserted in the experiment it required 120 cm drop height to initiate the RDX pellets. Significantly, although the impact pulse in the six striker experiment was considerably different in duration and character than the simple half sine wave generated by the no striker configuration, ignition of the RDX pellets occurred when nearly identical loading rates and stress amplitudes were attained in both experiments.

INSTRUMENTATION

The NSWC impact machine was designed to incorporate a variety of instrumentation to allow it to make measurements of the material behavior and ignition processes as they occur in the sample during impact. Measurements for these events are essential to an understanding of ignition under impact whether it occurs in small scale samples or in much larger full scale charges.

Presently, strain gages are the primary means of measuring the force of impact on the sample. These gages are located on the anvil to give the average force of the impact and some information on sample response. The response time of the gages now being used is approximately 1 μs. Strain gages have occasionally been mounted on the drop weight for specific purposes.

Accelerometers, mounted on the drop weight, are principally used as a check and calibration for the strain gages. The signals from these units are generally noisier and have poorer frequency response than the strain gages.

An optical thickness gage using a laser is used to measure the thickness of the sample during impact. This technique, shown schematically in Figure 3 can detect changes in sample thickness that occur on the

scale of a few tens of microns and in times shorter than 1 μs. It provides a direct measure of impact and rebound velocities as well as sample thickness and rate of change of thickness. This information allows the energies of impact and of rebound as well as the energy transferred to the sample-anvil-drop weight to be determined. Because it is non-intrusive and has no direct mechanical link to the impact machine, it is planned to use the laser thickness gage as a replacement for the strain gage by differentiating its output to determine acceleration of the sample.

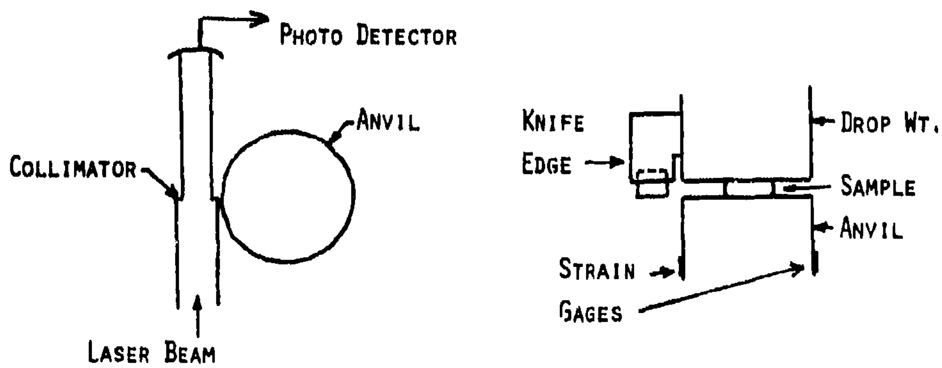

Figure 3. Schematic of Optical Thickness Gage

Pressure gages can be used to provide either a go-no go indication of reaction on impact or a more informative direct measure of the amount of gas produced. Either technique records only increases in gas pressure and is insensitive to the acoustic noise of the impact. As such, it is much superior to any acoustic device that might be used to measure the noise output of a reaction.

Infrared sensors have been used to measure the heat generated by both energetic and inert solid materials on impact. For these devices the impact machine was modified to include a sapphire or a silicon anvil through which the infrared device views the sample.

A heat sensitive film technique based on the transparent film made for vugraphs has been developed at NSWC to measure the spatial location and to estimate the temperatures of local hot spots and reaction sites that occur adjacent to the film's surface.[3,4,5] This technique, described in detail in the above references, has proved to be an extremely useful and informative tool; not only in impact experiments but in low level shock experiments as well.

SOME EXPERIMENTAL RESULTS

A rather surprisingly large number of experimental results have come out of this work. Many of these results were not anticipated and could not easily be explained by conventional theories. For some of these, new hypothesis have been advanced, while others remain to be explained.

At the onset of this work, it was realized that the experiments of Heavens and Field[6] at the Cavendish Laboratory in which they demonstrated the correlation between a sudden collapse of the sample and the start of ignition in crystals of HMX and RDX as well as other explosives, was indicative that the process of material failure was linked to that of hot spot formation. It is believed that this linkage most likely occurs via localized deformation associated with the material failure. It has been found at Cavendish[7] and at NSWC that surpressing the sudden failure of explosive crystals under impact, by surrounding them with the appropriate plastics, decreases their sensitivity. Thus, the sensitivity of the PBX's is less than that of their major explosive components because of the presence of the plastic matrix materials. More importantly, the explosive response to impact (which will be reviewed shortly) of many PBX's is considerably less than that of their main explosive component.

Most PBX's show little or no indication of sudden material failure under impact. A few experimental mixtures of PBX's and propellants did show indications of sudden material failure; these materials were generally more sensitive to initiation and more likely to produce a violent response due to impact. It is known from Russion work[8], that if the sudden failure. were to be suppressed by preventing flow through confinement, then an otherwise sensitive material could be made to appear very insensitive. Thus, impact machines that use a confined sample, such as the Rotter or Picatinny machines, will give different results than the Bruceton-ERL or the new NSWC machines that employ no radial confinement.

Experiments using the heat-sensitive film have shown a number of interesting and very surprising results. The experiment, as it finally evolved, consisted of a sandwich-like affair in which the sample pellet was placed between two sheets of heat sensitive film. Briefly, since these results have been reported elsewhere,[4,5] it has been shown that at threshold, ignition almost never occurs in the high pressure region near the center of the sample ($P > 10$ kb) but, when it occurs, ignition almost always occurs at or very near the low pressure region near the outer edge of the sample. This is the region of maximum shear and minimum pressure. Pressures in this outer region approach the yield stress the material which generally is quite low and can be as small as 150 psi for some PBX's and propellants. Among the two exceptions that have been noted to date is TATB, in which occasionally hot spots and some ignition sites have been observed slightly beyond the original radius of the sample disc. This may in part be due to the high loading rates which produced hot spots early in the sample expansion, and which afterwards were surrounded by the subsequent expansion of the sample. The other exception was seen in a series of impacts on propellant gum stocks. These materials, which contained 67% NG, cracked on impact. Ignition sites occasionally occurred along the crack surfaces. The cracks extended in a labyrinth like fashion and the occasional ignition event propagated along the crack. In summary, in both these experiments and in other large scale experiments, rapid shear and high rate deformation are the important elements in generating hot spots. Pressure appears to have little or no role to play other than to provide the driving force for these other processes.

In a set of rather interesting experiments, the explosive response of small samples ($\approx$35 mg) to impact induced ignition is measured. This is not a sensitivity test, the impact parameters are chosen to cause the initiation of a reaction in the samples (for example, a 5 kg drop weight released from 150 cm). The sample is impacted in a confined volume ($\simeq$ 120 mm^3), and the pressure generated by gas evolved in the reaction is recorded. The explosive response is measured by examining both the amplitude and rate of rise of the gas pressure. Those materials that respond violently, display a very large amplitude, steeply rising pressure pulse, $\approx$800-1000 psi in $\approx$1-5 μs. The less violent materials give responses of the order of 100 psi in 80-100 μs. In this way, it is possible to detect differences in the explosive response between similar materials such as would occur in slight modifications of a PBX as shown in Figure 4. Detection of the differences in the explosive response of two dissimilar materials is generally very easy. It now appears possible, with the explosive response technique, to provide guidance to the explosive and propellant formulators to optimally develop energetic materials insensitive to impact. However, at this time much

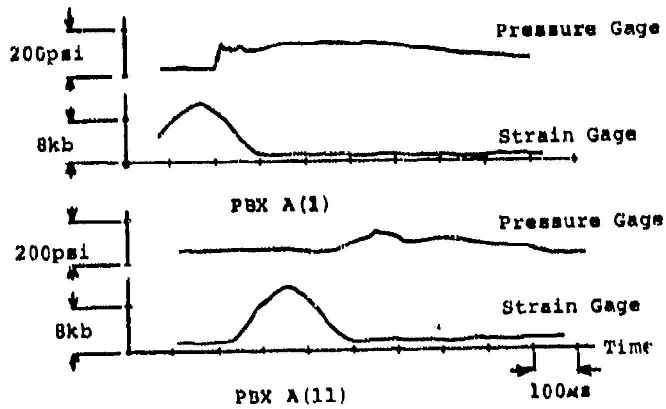

Figure 4. Explosive response of two similar PBX formulations.

more testing remains to be done to establish this premise with certainty. Finally, as a reminder, these experiments all measure response to impact, and there can be no certainty that similar responses would occur for other stimuli such as shock or heat.

THEORETICAL ASPECTS

The theoretical treatment of hot spot formation has focused on the localized deformation processes that occur in crystals and the localized heating associated with this deformation. This work has been developed elsewhere and will only briefly be described here. When a crystal undergoes rapid deformation and shear, the deformation is localized and occurs mainly along slip planes. Usually the deformation occurs along a number of slip planes which taken together form a shear band. The material on either side of the shear band essentially remains undeformed. In a series of papers, we have developed a theoretical treatment of the heating associated with the localized deformation.[9,10,11] Basically, the theory treats the local heating produced by moving dislocations that are generated in a crystal as it undergoes failure. Currently of interest, is the local heating produced at the tip of a propagating crack. At the crack tip, a similar dislocation motion occurs, and consequently, similar heating must occur.

CONCLUSIONS

Unfortunately, limited time and space have made it necessary to only briefly cover the topics of the review. However, much of what has been covered has been published in greater detail elsewhere or is in the process of being published.

We wish to convey the message that, if instrumented carefully and thoughtfully analyzed, the impact machine can be made to yield valuable information and insights into the processes responsible for the initiation of energetic materials by relatively low level impacts. Also, impact testing can be made to provide direction to the process of developing energetic material formulations that are minimally sensitive to impact. Finally, it now seems possible that the impact machine and its derivatives can be made to yield insights into the processes responsible for impact initiation of large scale charges. In fact, given the very high costs and difficulties of adequately instrumenting and interpreting large scale tests, and the necessity of obtaining a sufficient data base to reliably estimate explosive and propellant safety and survivability in an increasingly hostile and demanding environment, it seems inevitable that small scale impact-like tests must be developed to complement the large scale tests. This marriage can only be meaningfully achieved if the processes responsible for impact induced ignition are understood.

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